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PRINCIPLES OF ODOR RECOGNITION BY THE OLFACTORY SYSTEM APPLIED TO DETECTION OF LOW-CONCENTRATION EXPLOSIVES

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14. ABSTRACT
The Tufts Medical School Nose (TMSN) - a device based on the biological principles by which the vertebrate (canine) olfactory system functions - has been developed to detect the vapor phase signature associated with buried landmines. The device demonstrated it could detect concentrations of 300-500 parts per trillion of vapor phase 2,4 DNT, a compound that accompanies the TNT found in landmines. The TMSN was tested in chambers in association with the Canine Detection Unit at Auburn University and the results were slightly better than the thresholds for dogs detecting this compound. During field tests at Ft. Leonard Wood, MO, the device showed that in automatic detection mode it could detect the presence of the buried TMA-5 antitank and buried PMA-1A anti-personnel landmines placed in known locations. The TMSN also located buried PMA-1A anti-personnel landmines in a blind test in which the Tufts U. operators didn't know whether or not a mine (or how many mines) was present at nine marked locations. In the blind test, the device correctly found four landmines that were present and made two false positive errors.

15. SUBJECT TERMS

ODOR RECOGNITION	LOW CONCENTRATION	LANDMINES	BURIED MINES
OLFACTORY SYSTEM	SIGNATURE DETECTION	BURIED EXPLOSIVES	
EXPLOSIVES	VAPOR PHASE	BURIED MINE DETECTION	
DETECTION	ANTITANK MINES	ANTIPERSONNEL LANDMINES(APLM)	

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Preface

The premise of this study was based on the fact that dogs can be trained to find buried landmines. This project built on the many years of study applied to analysis of the vertebrate olfactory system, to use these biological principles to design and build an artificial olfactory system (see Fig. 1).

This report details the work performed under the Defense Advanced Research Projects Agency, contact number C-DAAK60-97-K-9502, during the period April 1997 to June 2001. The U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, Natick, MA, monitored the study.

PRINCIPLES OF ODOR RECOGNITION BY THE OLFACTORY SYSTEM APPLIED TO DETECTION OF LOW-CONCENTRATION EXPLOSIVES

Summary

The Tufts Medical School Nose (TMSN) – a device based on the biological principles by which the vertebrate (canine) olfactory system functions – has been developed to detect vapor phase signatures associated with landmines. The device demonstrated it could detect concentrations as low as 200-500 parts per trillion of vapor phase 2,4 DNT, a compound that accompanies the TNT found in landmines. The TMSN was tested in chambers in association with the Canine Detection Unit at Auburn University and showed that its sensitivity was slightly better than the thresholds for the average dog in detecting t2,4 DNT, tested in the same chamber. During field tests at Ft. Leonard Wood, MO, the device showed that, in automatic detection mode, it could detect the presence of buried TMA-5 antitank and buried PMA-1A anti-personnel mines placed at known locations under certain environmental conditions. The TMSN also located buried PMA-1A antipersonnel landmines in a blind test in which the Tufts operators did not know whether or not a mine (or how many mines) was present at nine marked locations. In this blind test the device correctly found the four landmines that were present and made two false positive errors.

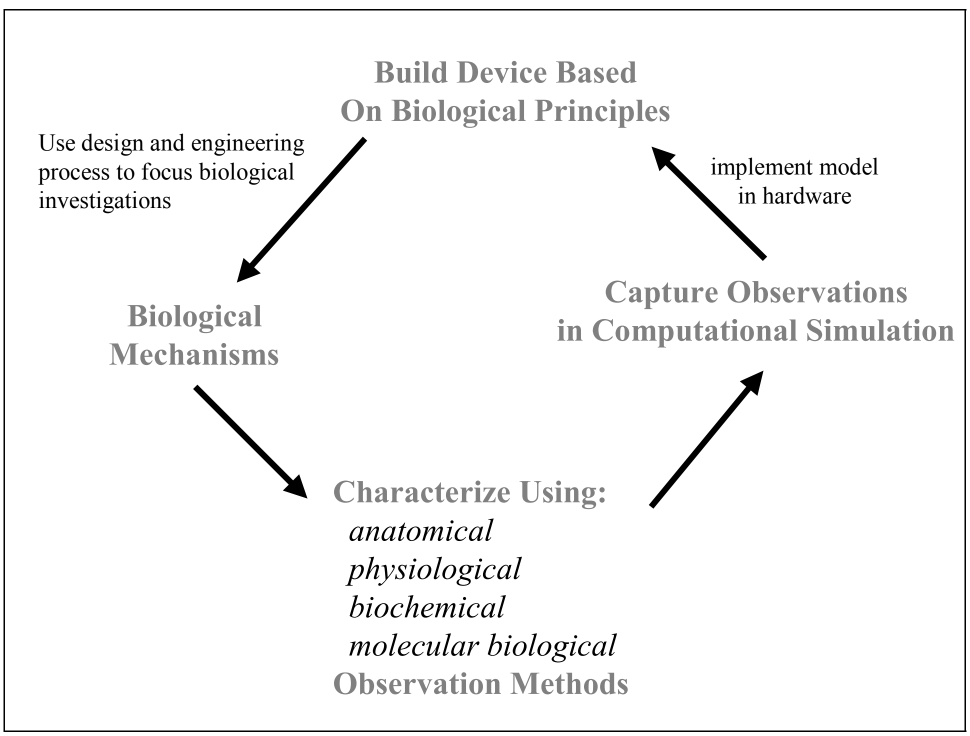

Fig. 1. The developmental philosophy of the Tufts' team for finding landmines was to assemble an artificial olfactory system based on biological principles.

Introduction

Background

Among the investigators who study the sense of smell, the prevailing view is that odorous, volatile compounds are detected by vertebrate nervous systems via mechanisms that rely on distributed, combinatorial representation of molecular structure (see Fig. 2). In this scheme an individual receptor (or sensor) is not specifically sensitive to the overall structure of an odorant, but rather one receptor binds to one molecular subcomponent, recognition attribute, or epitope in analogy with immune system recognition of antigens. For full recognition of even a pure compound such as TNT, multiple receptors (sensors) are thought to bind multiple recognition attributes on each molecule. Detection and recognition emerge from analysis of the patterns of activity in time and space generated across the arrays of the activated receptors (sensors) and higher order cells. Association of these activity patterns with a particular compound (or mixture, such as the complex odor of a rose) occurs in and is dependent on the integrative neuronal circuitry of the olfactory pathway in the brain. Tufts' researchers have termed this molecular recognition process 'distributed specificity'.

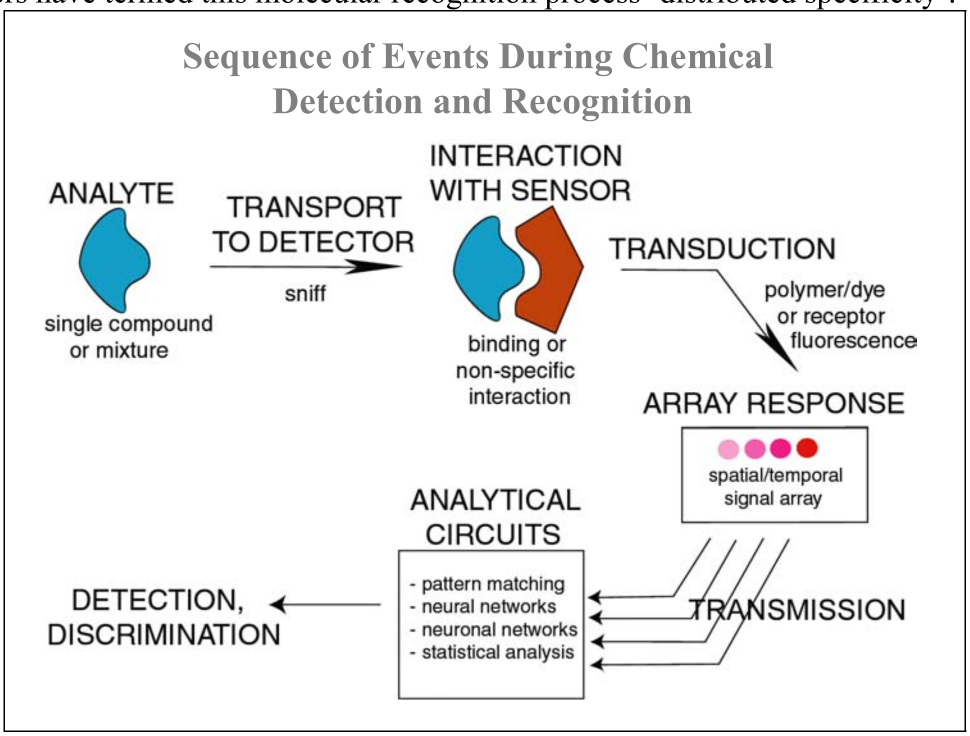

Fig. 2. The sequence of events that must occur in order for chemical recognition of air phase compounds to be detected in both biological and artificial olfactory systems.

The advantages of such a distributed system include: a) the nature of compounds to be detected need not to be known in advance for specific receptors to be generated for them; b) detection of multitudes of compounds is possible with many fewer receptors than there are compounds; c) fault tolerance due to inherent redundancy; d) resistance to injury due to redundancy; e) flexibility of response following changes in developmental or environmental

variables; f) good recognition in noisy environments; and g) trainability, based on experience, of the system to complex chemical signatures.

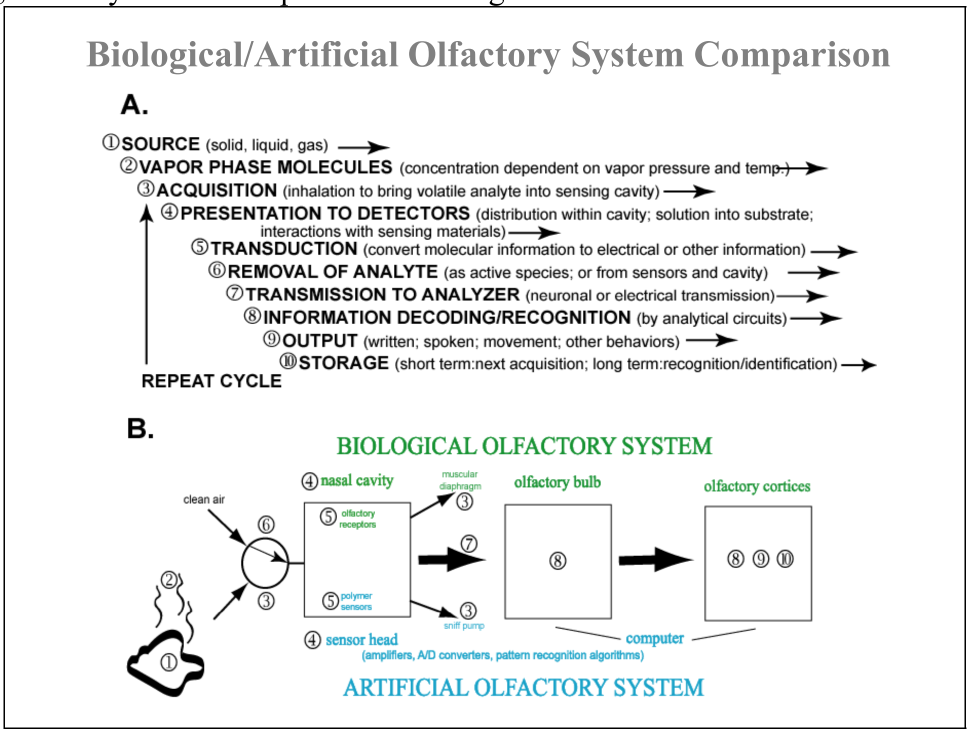

Fig. 3. A. Specific steps that are carried out in the vapor detection process. B. Comparison of how these steps occur in biological and artificial systems.

In this proposal we have studied the detailed mechanisms by which the olfactory system achieves *low concentration response* with *high discriminability* and we have implemented these mechanisms in the optically-based, artificial olfactory system developed in our laboratories. In our system we have incorporated sensors based on the interaction of analytes (odors) with mixtures of various polymers and fluorescent dyes and we have developed analytical networks based on brain circuits. The use of changes in fluorescence as the output signal has the advantage of providing multiple measures of response including changes in intensity, time course, fluorescence lifetime, and wavelength.

Operational Definition and Scope

The goal of this project was to incorporate as many biological principles of olfactory function as possible (see Fig. 3) into an artificial device that could be man carried, have low power requirements, operate at more or less real time (discrimination at walking speed), be robust for field use, and could identify and discriminate the vapor phase signatures of anti-personnel landmines in the field. The technical features of the Tufts' device include:

1. lightweight: ~5 kilos with batteries; power consumption not yet optimized, probable reduction to <2 kilos.
2. relatively inexpensive components: <$2,000
3. rapid response cycle between discriminations: ~3-6 s

4. sensor cavity and sniff generator about size of baseball bat; computer about size of 2 shoe boxes

5. portable, designed for hand held use against the ground, where odorant concentrations are highest

6. delivers analytes to sensors by negative pressure sniffing from ambient environment

7. sensitivity for nitro aromatic compounds, including TNT and DNT: ~ 0.1-1 ppb or $\sim 10^{-11}$ M

8. good discrimination among certain compounds: detection of single carbon atom differences between analytes in certain homologous series.

9. discrimination based on several different analytical algorithms

10. spoken word output

11. features are based on mammalian olfactory system

12. numbers of sensing sites (see Fig. 4) can be varied by size of sensing cavity and number of sensors used for any one task can be dynamically modified under software control.

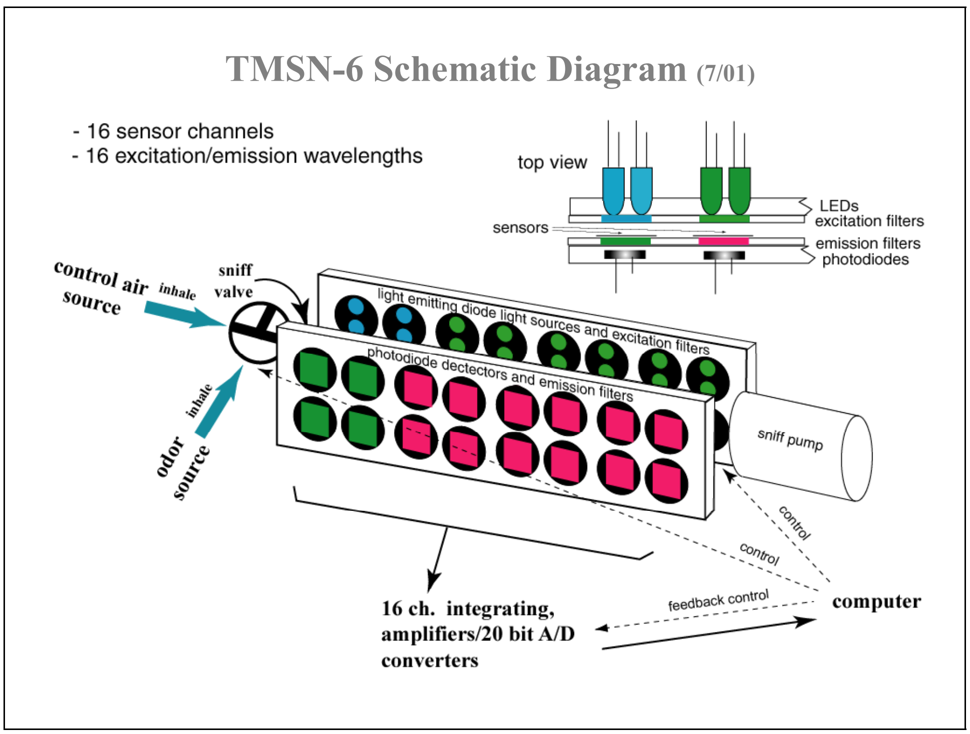

Fig. 4. The TMSN devices essentially consist of arrays of microspectrofluorimeters (in this case 16) that are tuned to observe the changes in fluorescence of reporter dye molecules attached to or intrinsic to various polymers. These polymers change the degree and polarity of their fluorescence emissions when vapor phase substances (odors) are drawn over them. In the design shown above, the sniff pump draws either clean or odorized air (depending on the position of the sniff valve) over the sensor array. Fluorescence changes are observed by the photodiodes, digitized an stored in computer memory (see Fig. 7).

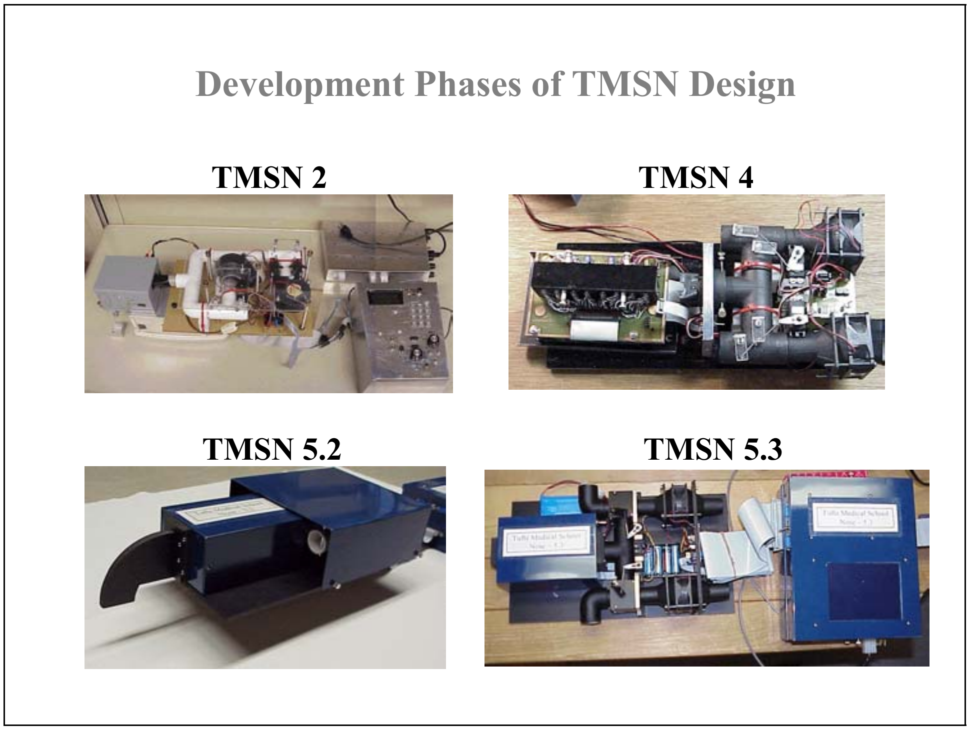

Fig. 5. Phases in development of the TMSN devices.

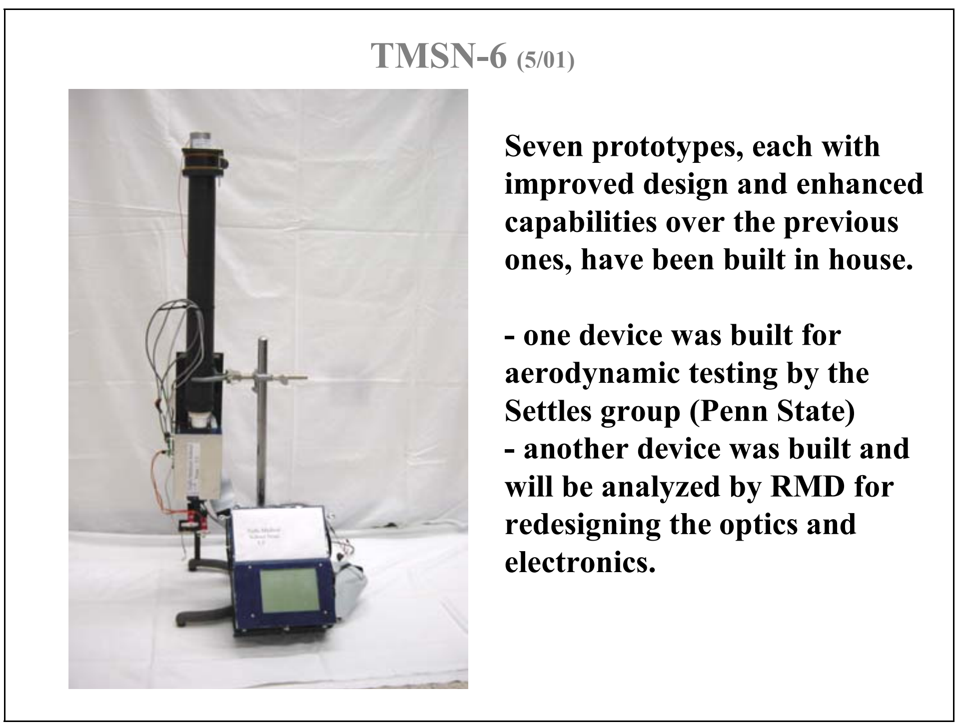

Fig. 6. The most recent TMSN device

Results

The device has been evaluated with respect to the flow properties of the sensor cavity (see Fig. 7, 8) in collaboration with Gary Settles, PhD at Penn State; with regard to its discriminative abilities and limits of detection (see Fig. 10, 11)in collaboration with Paul Waggoner, PhD at the canine detection of Auburn University; with regard to detection properties and limits in our laboratory with our odor delivery devices; and in a landmine test site set up by DARPA at Fort Leonard Wood. Results from these studies are illustrated below.

<u>Sensor cavity flow studies</u> (please click on figure to see attached *.mpg movie).

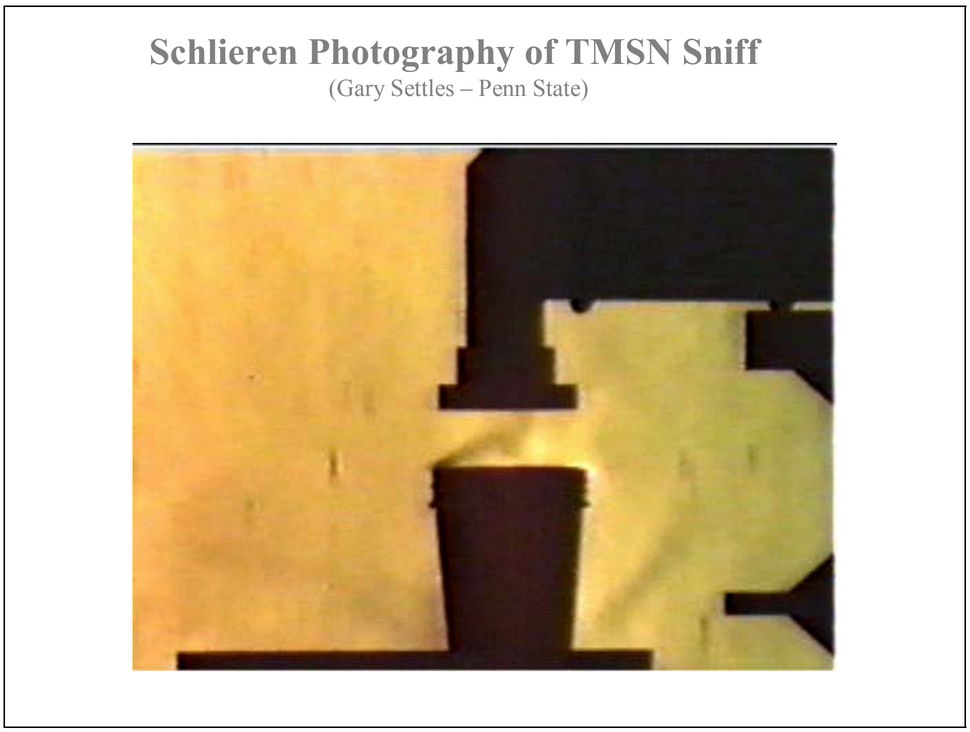

Fig. 7. Schlieren photograph/movie showing exhalation then inhalation of acetone vapor into the snout of TMSN-5.

Schlieren analysis (see Fig. 7) of flows into and laser sheet analysis (see Fig. 8) of flows within a transparent model of the sensor cavity have allowed analysis of the access of vapors to the sensor array. Sensors have been shaped and placed in optimized positions to improve signal size and consistency from trial to trial. These studies are still ongoing.

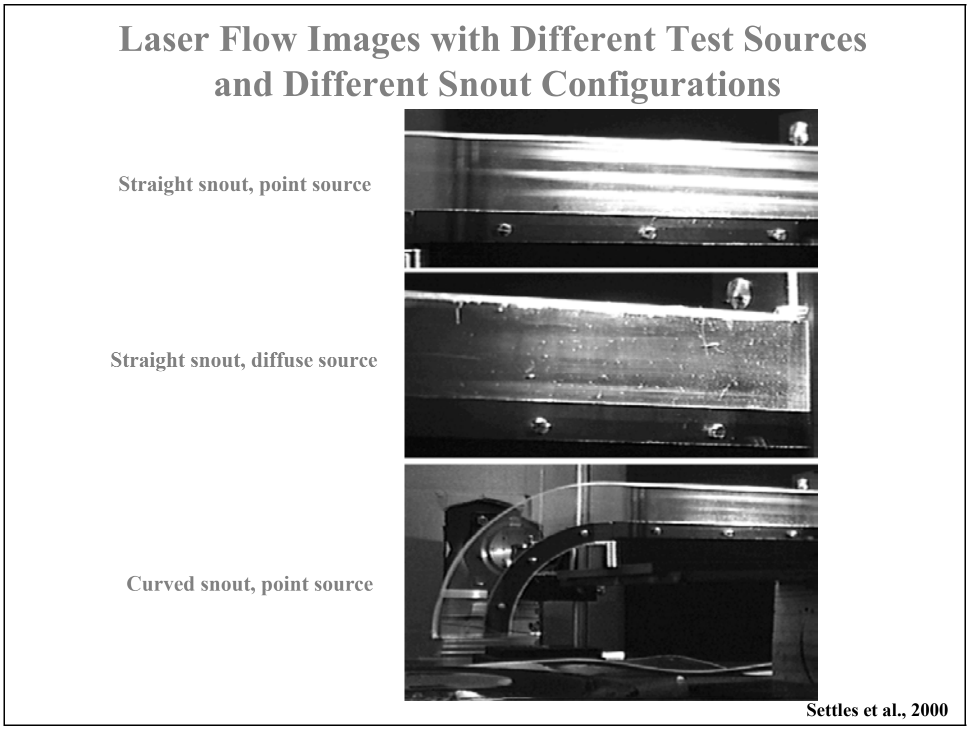

Fig. 8. Laser sheet illumination analysis of flow of smoke within transparent sensor cavities of different shapes and with different flow rates.

<u>Sensor array responses when different vapor phase substances are applied. Note these are 1 s pulses.</u>

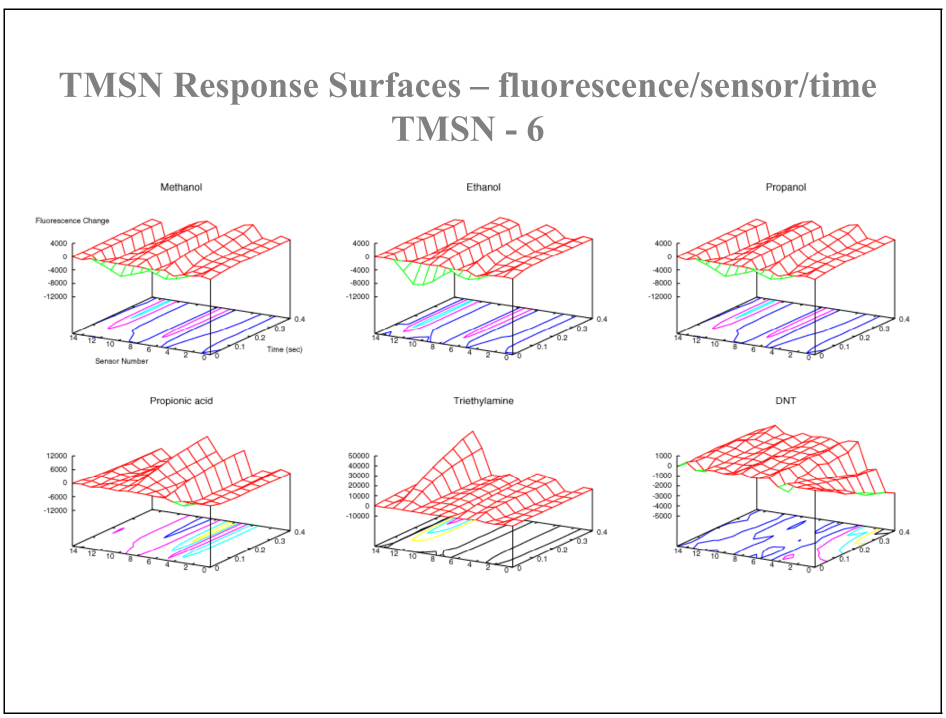

Fig. 9. Response surfaces from a TMSN device with 16 sensors stimulated with 1 s pulses of 6 different vapors. Note rapid response, distinctive profiles with each compound

and sensitivity to dinitrotoluene (DNT) in lower right panel.

<u>TMSN devices tested in highly controlled and calibrated canine test facility at Auburn University.</u>

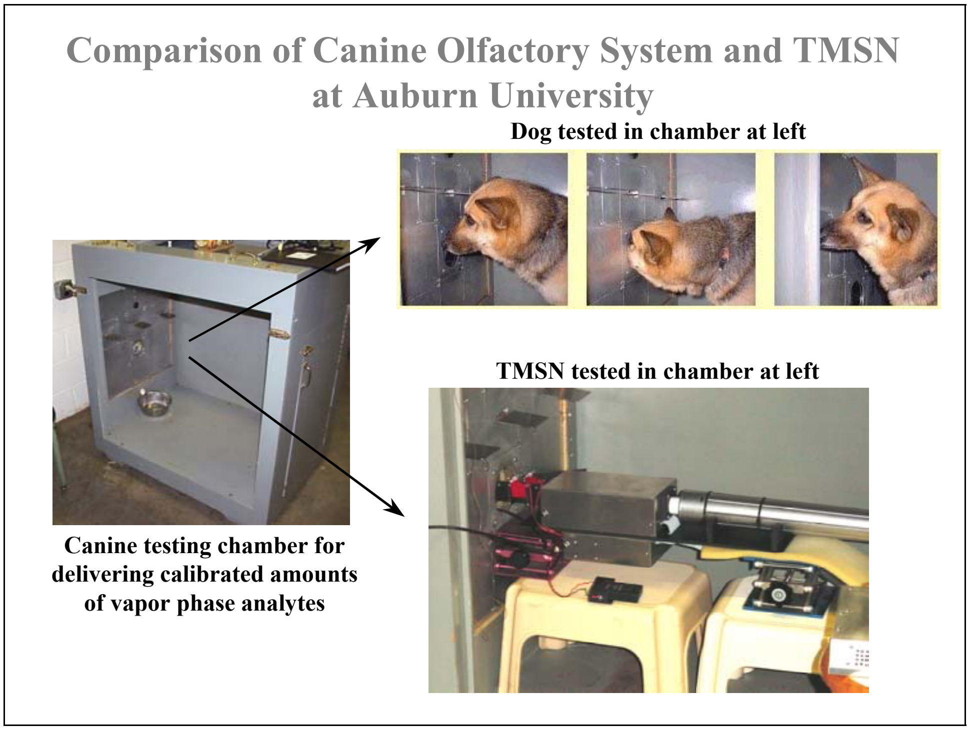

Fig. 10. TMSN devices were tested in the same chambers used for testing dogs. These chambers deliver odors under highly controlled conditions and the concentrations and purity of the delivered compounds are verified after each test by gas chromatography/mass spectrometry analysis. This method was used to generate the data shown in Fig. 11.

When tested with controlled concentrations of 2,4 DNT, a major constituent of TNT landmines, it was found that the dog's performance threshold was on the order of 1-5 parts per billion (red line Fig. 11) whereas the TMSN device threshold was on the order of 0.3 to 0.5 parts per billion. Since these tests we believe we have improved performance another two fold or so.

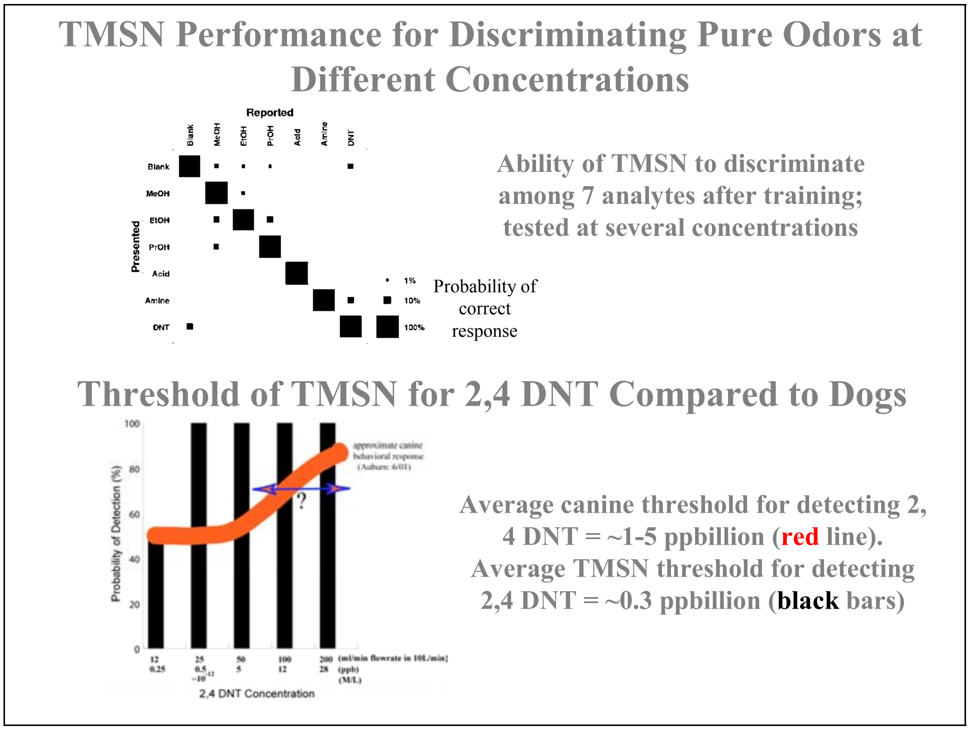

Fig. 11. Top: TMSN performance in discriminating among odors in the automatic detection mode. The device was trained at one concentration for the compounds listed on the vertical axis and was then required to categorize vapors presented at different concentrations as one of the trained compounds as plotted on the horizontal axis. Note that probability of correct response is very close to 95% for all compounds despite being trained on a single concentration. Bottom: Performance of dogs and TMSN-6 device in threshold tests for 2,4 DNT. 50% performance is chance for both dogs and the artificial olfactory system.

Tests performed in the field at Fort Leonard Wood.

We have carried out a number of tests on buried landmines (without fuses) at the DARPA landmine test site at Fort Leonard Wood.

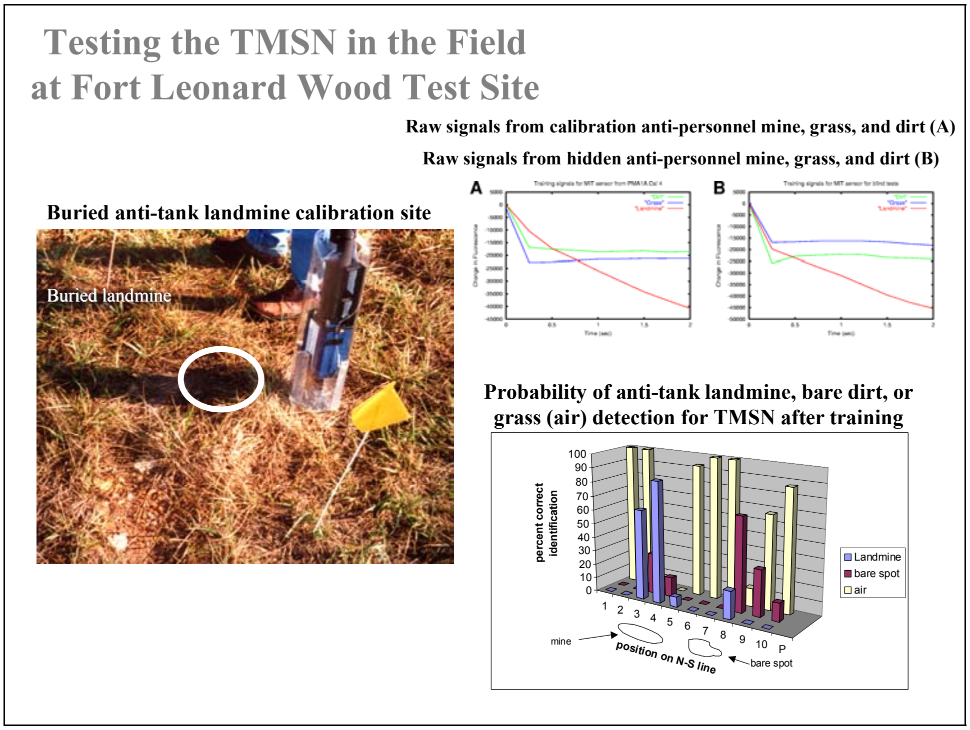

Fig. 12. Automatic detection of the 2,4 DNT vapor signature of a calibration site anti-tank TMA-1A landmine at Fort Leonard Wood. The mine was buried between the two flags as shown at the left. A. and B. to the right show the different responses of sensors designed by Tim Swager (MIT) for nitroaromatic compounds to tests in the field over grass, over the landmine, and over a bare dirt spot. Note the different responses between landmine and other sites. Below right: these are results from automatic recognition of the landmine position after training the TMSN device to discriminate among the mine signature, air (grass) or dirt spot. Note the probability of detection when the device was placed at different sites along a scan line that included the background grass, the mine location, and the dirt spot.

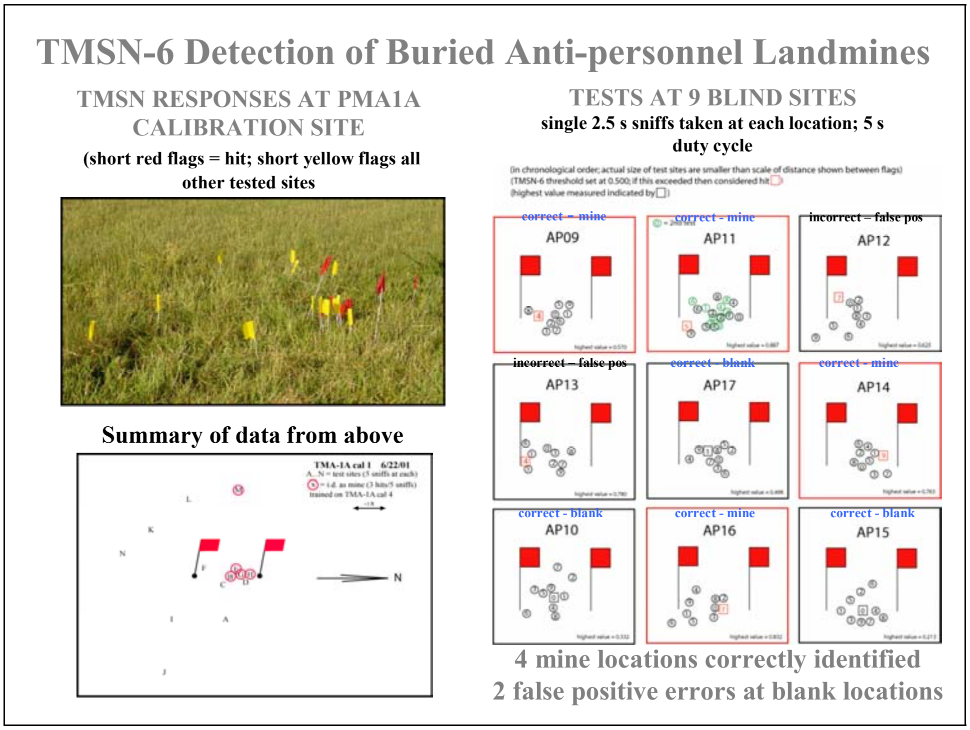

Fig. 13. Tests of TMSN device on buried antipersonnel PMA1A mines at Fort Leonard Wood. Left: calibration site test for automatic detection of a PMA1A after training on known mine location between flags. Note in left, bottom positions where device indicated the presence of a mine. One false positive was evident at site 'M'. Right: Blind test at 9 flag marked locations at which the Tufts operators did not know whether or how many PMA1A's were buried. These raw data show all positions that were sniffed at. The TMSN device detected all the mines that were, after the test, indicated to us were the positions in which they were actually buried. The device made two false positive errors.

<u>Summary of Results:</u>

Briefly we have incorporated more than 20 attributes of the biological olfactory system into an artificial device that is designed to exploit these principles for finding and identifying the vapor phase signatures of buried landmines. These attributes include:

1. Use sensors with broad response spectra distributed within the space of the sample chamber.

2. Sensing device exerts control over environmental attributes of the vapor phase stimulus – humidity, temperature, position in the ambient environment (restricted zone to which sniffing is applied).

3. The vapor phase stimulus is delivered to the detectors in a temporally controlled manner (onset, rise time, duration, fall time, individual sniff frequency, sniff bout frequency).

4. Use temporal profiles of sensor response in pattern analysis algorithms. Temporal patterns governed by both sniffing paradigm, by detection circuitry, light exposure parameters (duration, intensity, wavelength, rise and fall times), and by response properties of sensing materials.

5. Feedback control is exerted over the odorant delivery process in real time when using multiple sniffs per test trial; later sniffs are modulated based on information arriving in early sniffs.

6. Control over the adaptation characteristics of the detectors is accomplished by using short pulse stimulus administration and by brief and controlled exposure of the detectors to the light source (normalized and controlled bleaching).

7. Monitor long term changes in sensors/detectors in order to compensate for deterioration.

8. Consideration of which cross-reactive sensors to use is based on their shapes and sizes in ‘odor space’. Design of detection system and analytical algorithms is based on the nature of the odorants to be detected.

9. Maximize gain and distance from other sensors in ‘odor space’ by using measurements of detector response that change non-linearly and are orthogonal to one another along ‘odor space’ dimensions.

10. Control over sensor material sensitivity is accomplished by a) increasing the surface area of the sensor material; b) increasing surface area and properties of the photodetectors; c) improving intrinsic sensitivity of sensor materials.

11. Stabilization of sensor materials and responses by continuous oscillatory application of ambient odors and of target analyte. Continuous sniffing throughout test session.

12. Multiple sensor mechanisms are used for detection (intrinsic fluorescence of designed materials; fluorescence provided by addition of extrinsic dye).

13. Data from sensors are selectively weighted by feedback from analytical algorithms (presently accomplished by manual feedback) to optimize the information content that each sensor contributes to defining the odor signature.

14. Control over the gain characteristics of the detector circuits is accomplished by measuring dF/dt (change in signal from new baseline) after baseline reset upon light exposure rather than by using absolute signal amplitude.

15. Ambient odorant interference is controlled by subtraction of background (adaptation).

16. Information transfer from the detectors to analytical circuits is clocked by the sniff cycle. Clocking is used in analytical algorithms (stochastic resonance).

17. Convergence of input from multiple identical sensors is used to improve signal to noise ratio using simple addition.

18. Analytical algorithms are based on biological neuronal circuits (algorithms have been developed, but not yet implemented, in the functioning device).

19. Recognition and identification emerge from repeated (and continuous) training with feedback (‘reward’ contingency).

20. Recognition templates are stored in a library in random access memory.

21. Output by spoken word.

Conclusions and Recommendations

As demonstrated above, the TMSN, under certain optimal field conditions, can automatically, without operator intervention, find and identify the vapor phase signatures of landmines. The identification of these vapor signatures is partly dependent on sensitivity for 2, 4 DNT, a chemical compound that is always found in the presence of TNT, and partly on detection of other complex odor signatures to which our device is trained. We believe these results provide strong evidence that this approach toward finding landmines is valid and that with further development, field deployable devices can be made a practical reality. Development of this device will be continued.

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